Charakterisierung des Strömungsfelds eines Ranque-Hilsch-Wirbelrohrs mittels gefilterter Rayleigh-Streuung

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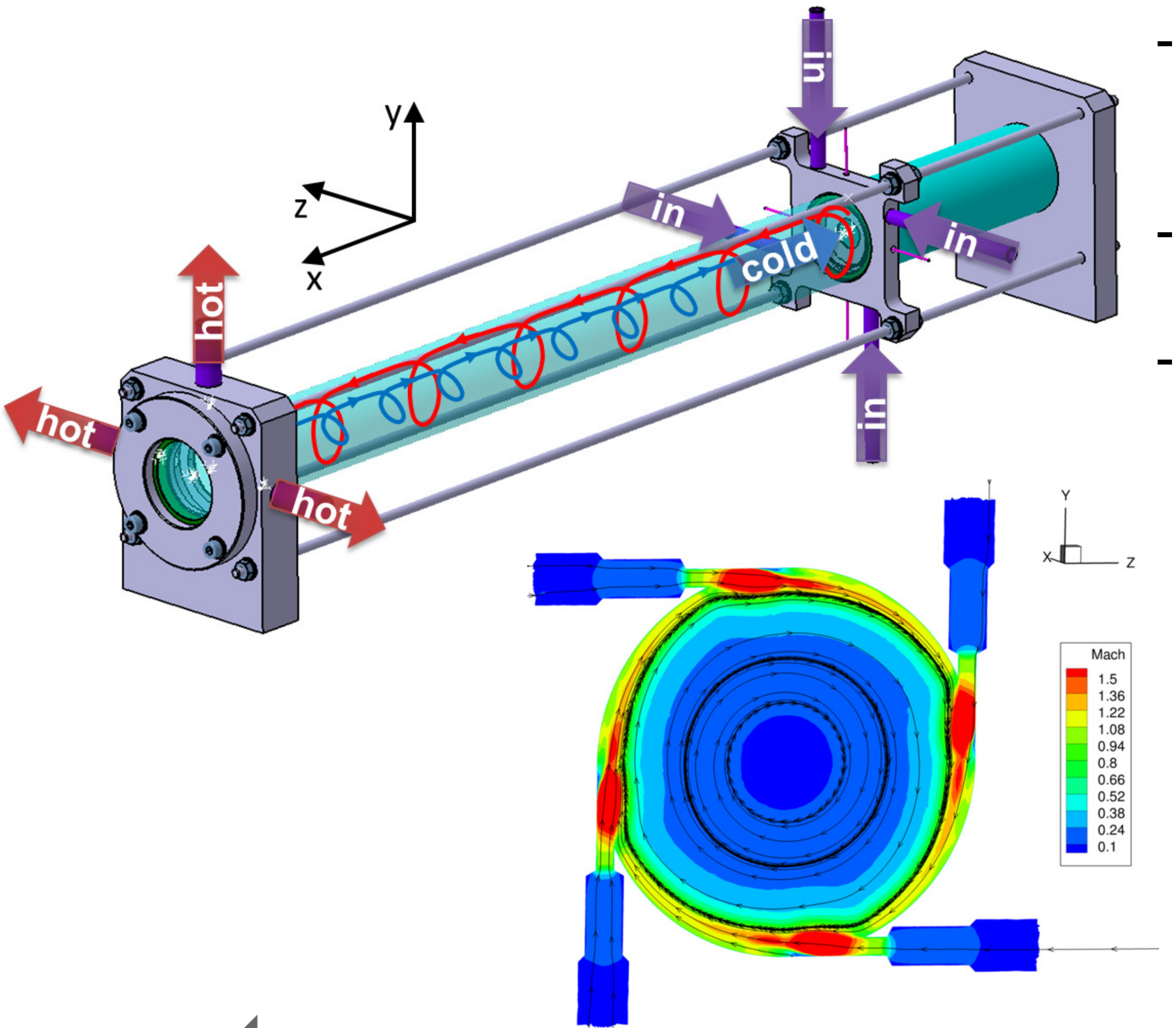
Ranque-Hilsch vortex tube (RHVT)



- Purely fluid dynamical → Simple geometry, no moving parts
- Temperature separation still controversially discussed
- Complex 3D flow
  - Adiabatic expansion
  - Radial compression
  - High vorticity
  - Viscosity and turbulence
  - Static temperature gradient
  - Convective heat transfer
  - Nonlinear acoustics

Outline

- Motivation
- FSM-FRS technique
- Experimental setup
- Measurement results
- Discussion and summary

Motivation

- Most studies rely on conventional probe based technology (Pitot probes, thermocouples, hot wires, etc.)
  → High temporal resolution, but: only point-wise, blocking impact (3 – 26 % of cross section) on the flow field

- Laser based optical measurement techniques → Noninvasive
  - Scattering from tracer particles added to the flow
  - Molecular scattering

- High centrifugal acceleration → discrepancy between fluid and particle motion

- Planar FRS → based on elastic molecular scattering

- Provides time averaged information on pressure, temperature and velocity (Doppler shift)

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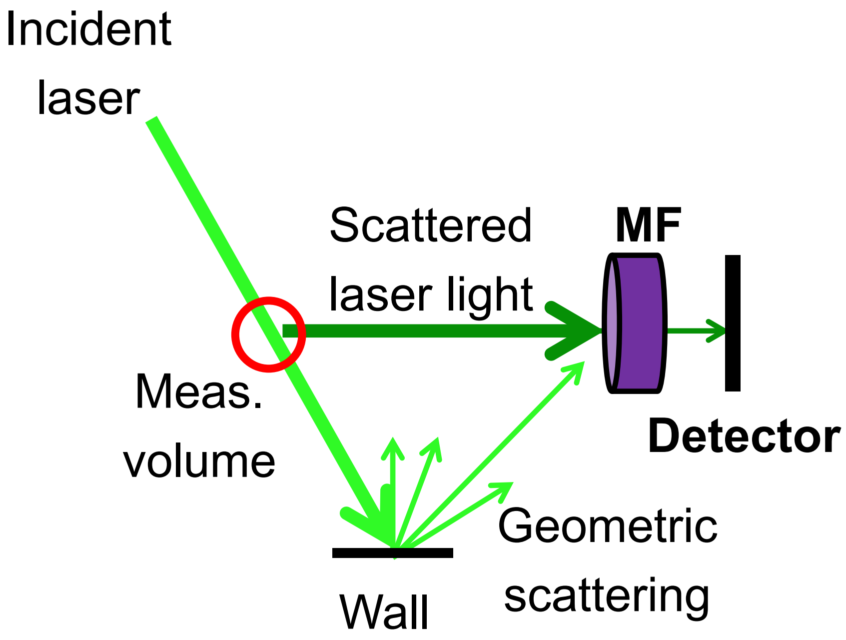
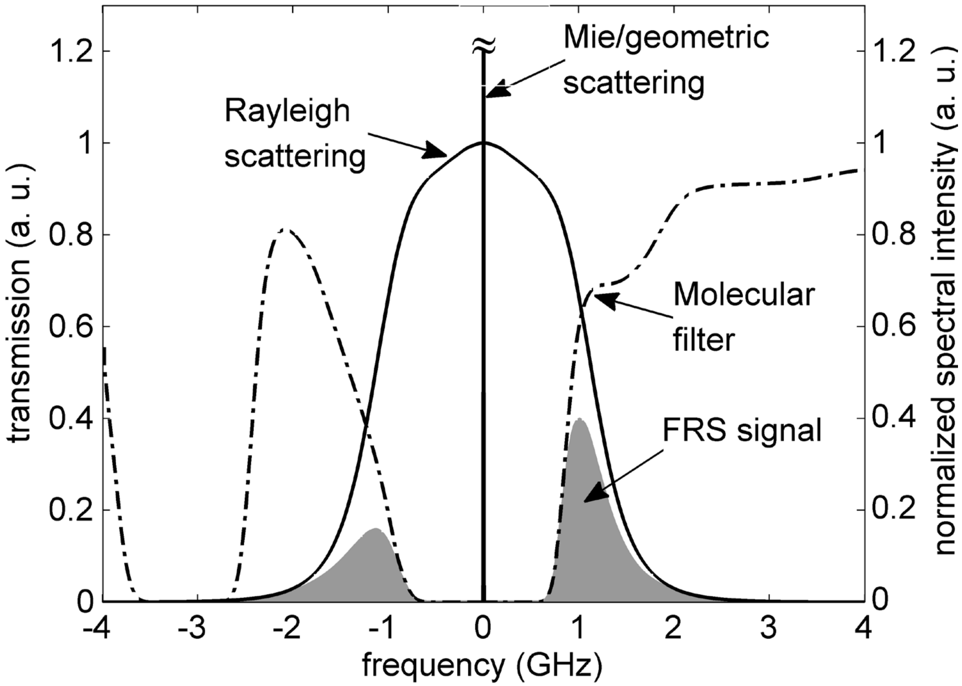
FSM-FRS technique | Working principle





- Molecular filter (MF) suppresses scattering from surfaces (geometric) and large particles (Mie)
- Portions of the spectrally broadened Rayleigh scattering reach the detector
- $\rho, p, T, \Delta\nu$ in FRS signal → lost due to on-chip integration

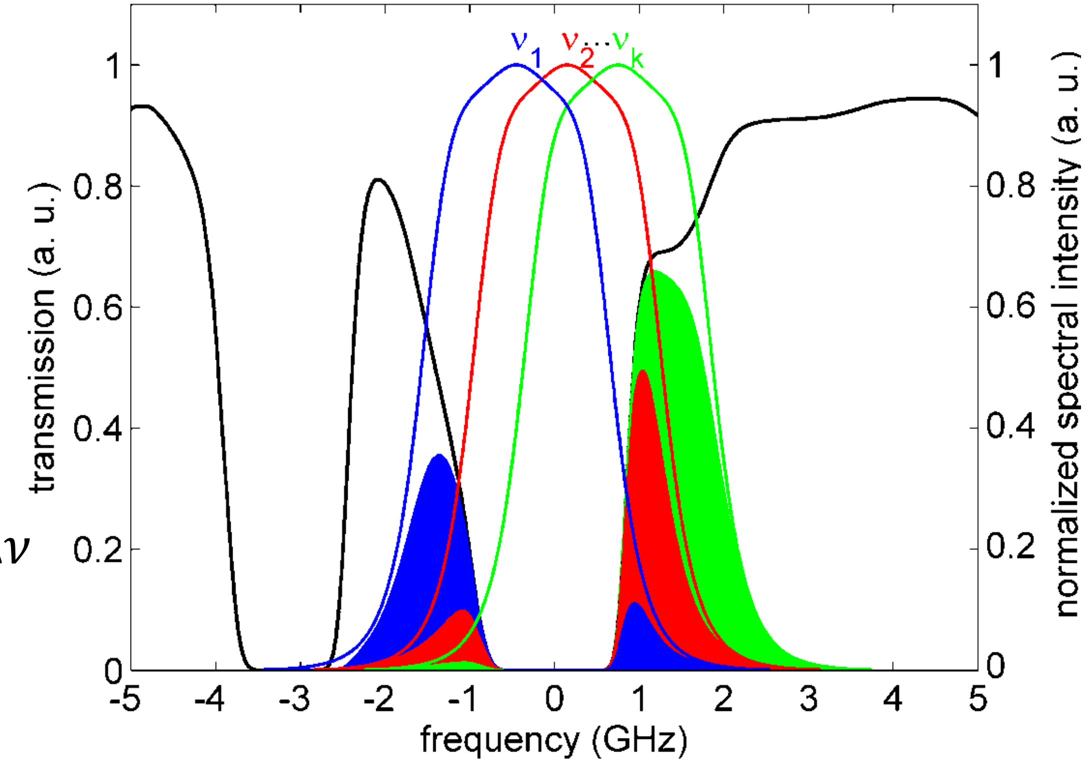
FSM-FRS technique | Frequency scanning method

- Spectral distribution is preserved for a stationary or temporally averaged process

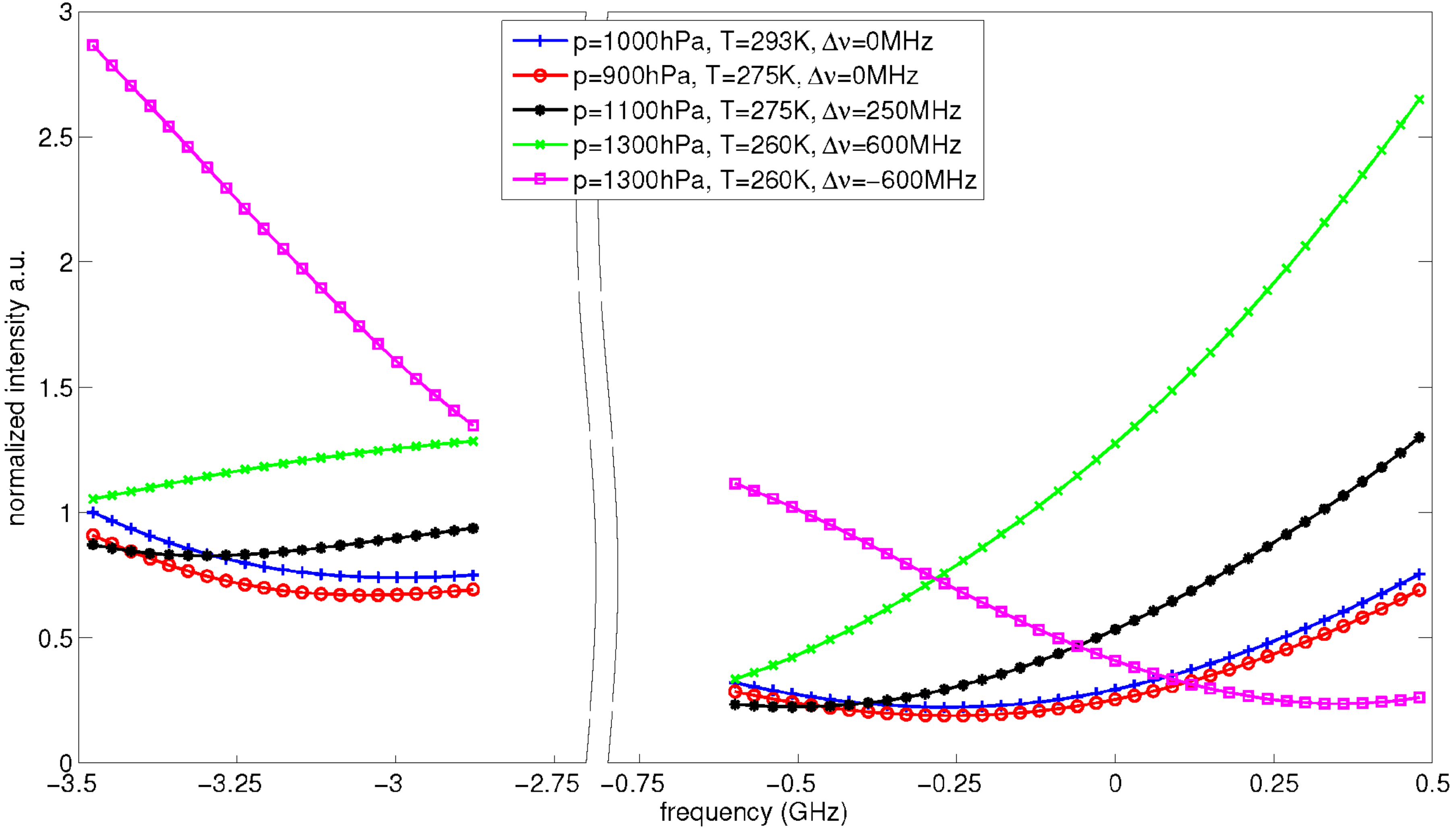
- Laser is tuned to discrete frequencies along transmission curve, FRS signal is altered

- Intensity spectra for each camera pixel

- Inverse problem: spectral lineshape is recovered by least-squares fitting $\rho, p, T, \Delta\nu$

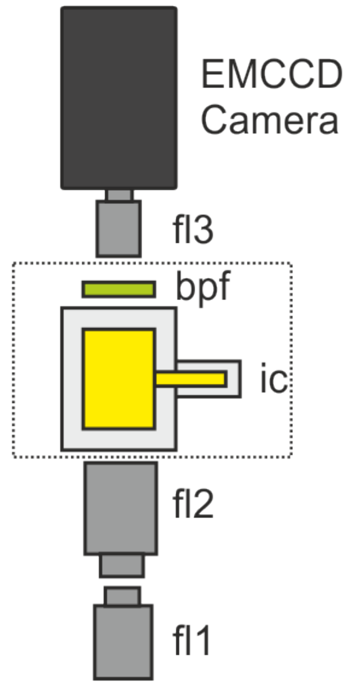


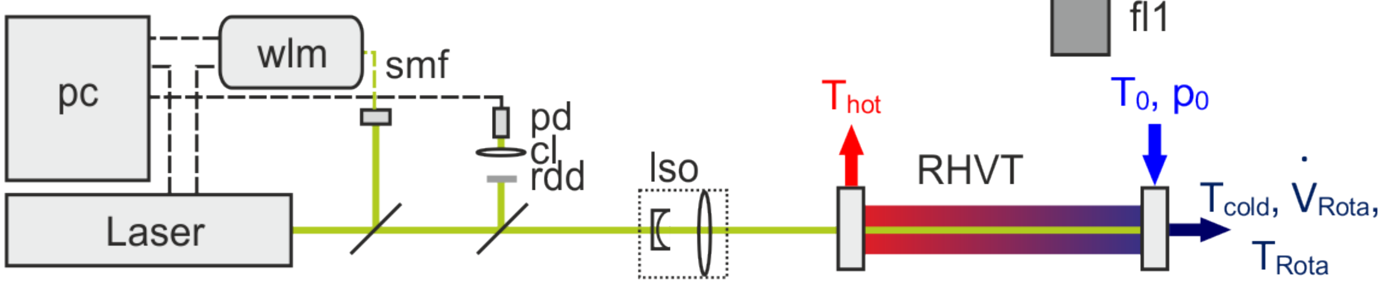
FSM-FRS technique | Frequency scanning method



Experimental setup

wlm:	wavelengthmeter	RHVT:	Ranque-Hilsch vortex tube
smf:	single-mode fibre	fl1:	focusing lens 1, 75 mm, f = 1.8
rdd:	rotating diffusion disc	fl2:	focusing lens 2, 100 mm, f = 2
cl:	collecting lens	ic:	iodine cell
pd:	photodiode	bpf:	bandpass filter, FWHM = 1 nm
lso:	light sheet optics	fl3:	focusing lens 3, 75 mm, f = 1.8





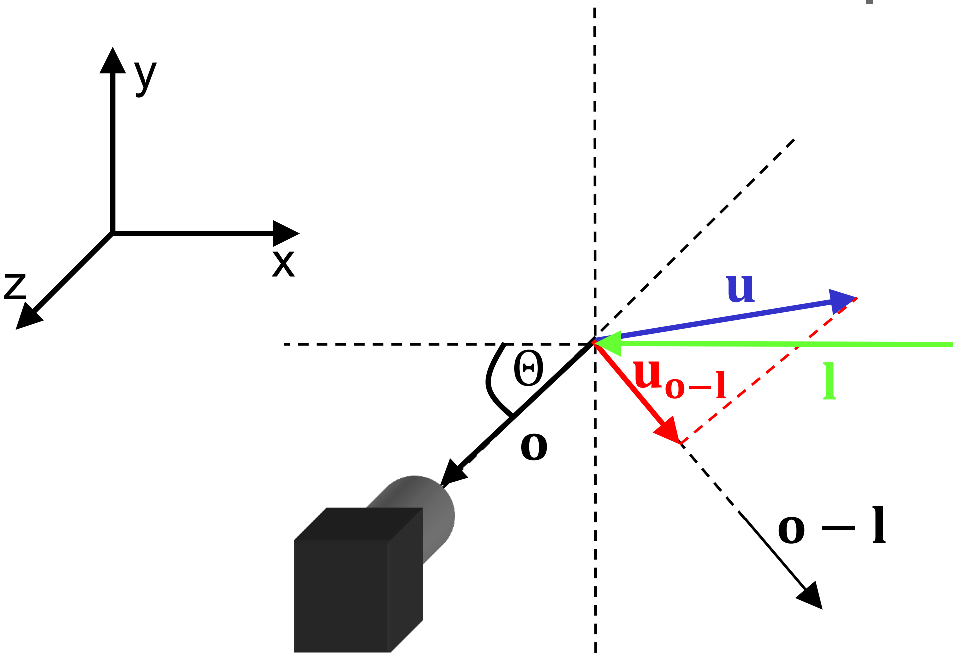
Light sheet:
- Cw (5W), scanning
- Height 32 mm
- Waist 0.6 – 2 mm

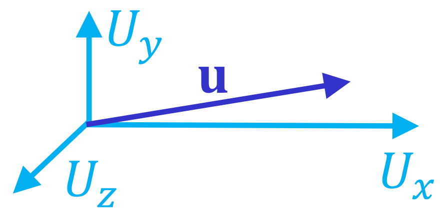
Field of view
- 53.5 x 53.5 mm^2
- 0.21 mm/pix
- Traversed 14 times

Frequency-scan:
- 32 frequencies
- Increment 60 MHz
- Exp. Time 6 s

Operating condition:
- $p_0 = 7115\ hPa$
- $T_0 = 294\ K$
- $\boldsymbol{\epsilon = \frac{\dot{m}_c}{\dot{m}} = 0.3}$

Measurement results | Doppler shift

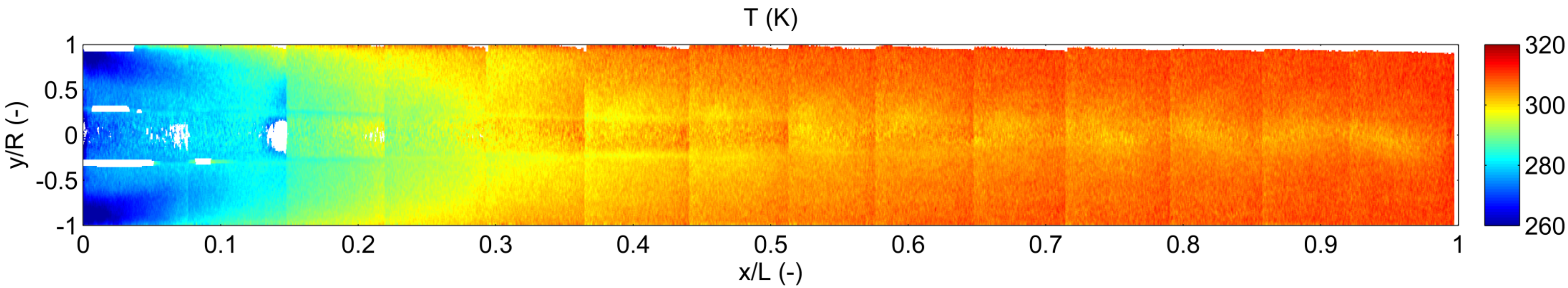




- No sensitivity to U_y
- Flow field rotationally symmetric with respect to the tube axis
- $\mathbf{l} = (-1,0,0), \mathbf{o} = (o_x, o_y, o_z)$

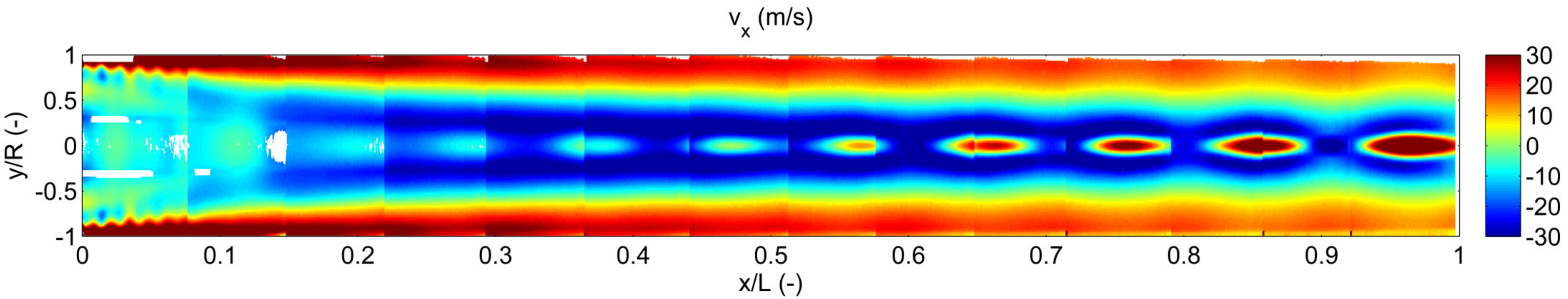
$$\boxed{U_x = \frac{c(\Delta\nu(y) + \Delta\nu(-y))}{2\nu_0(o_x - 1)}, U_z = \frac{c(\Delta\nu(y) - \Delta\nu(-y))}{2\nu_0 o_z}}$$

Measurement results | Temperature



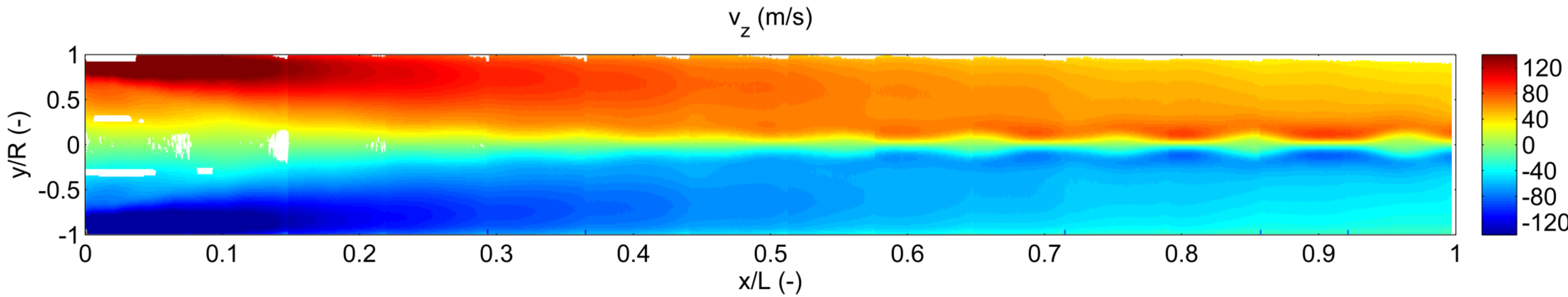
- Lowest temperatures (~ 240 K) near the injection
- Conical structure of the temperature field in the first third
- Centerline Temperature rises from 270 K near x/L = 0 to 294 K (inlet temperature) at x/L = 0.3
- Highest temperatures (~ 310 K) near the hot exit
- Declining temperature difference between core region and periphery, but: colder core persists as far as hot exit

Measurement results | Axial velocity



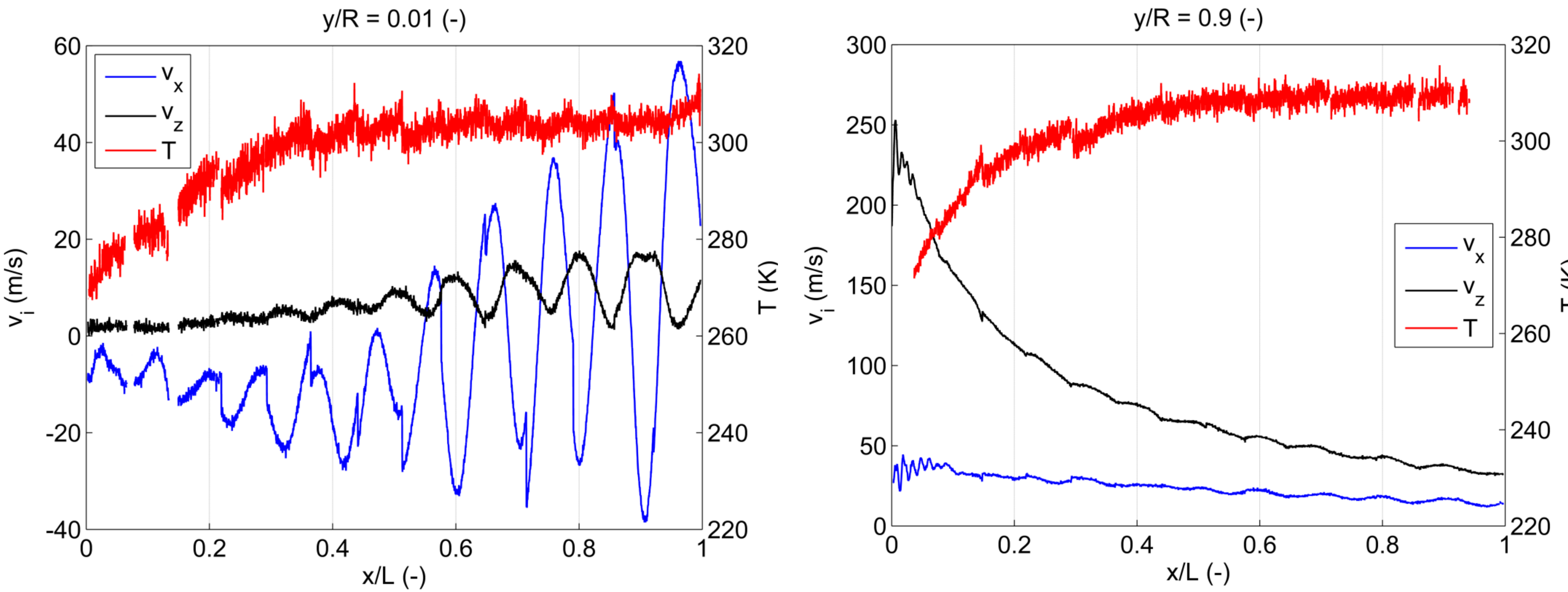
- Two main regions: peripheral and core area
- Sign change at the borderline between core and periphery → air streams back towards cold exit
- Core region more developed near the injection → similar cross sectional area in the back
- Regular flow pattern near the tube axis
  - Distinct zones, velocity differs from surrounding fluid
  - “Washed out” until x/L = 0.3 → ellipsoidal shape with growing axial distance
  - Velocities inside and outside negative in the front half
  - Kernels of positive axial velocity in the rear

Measurement results | Circumferential velocity



- Dominated by the swirl of the main vortex
- Highest values near the tangential air injection, decreasing gradually with axial distance
- Regular flow pattern also recognizable → expands the low velocity region around the tube axis

Measurement results | Axial profiles



- y/R = 0.01: Axial and circumferential velocities bear reminiscence to a driven oscillation, growing amplitudes towards hot exit
- Bulk temperature increase in the first third
- Discontinuities: Circumferential velocity seems unaffected, temperature and axial velocity are biased → strong relationship between heat release and axial velocity

Discussion and summary

- The flow field of a Ranque-Hilsch vortex tube was characterized with FSM-FRS for $\epsilon = 0.3$

- Temperature, axial and circumferential velocity fields were obtained

- Regular flow pattern was discovered
  → Indicates relationship between acoustic phenomena and the time-averaged flow field

Thank you!

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Explaining the temperature separation | A selection of hypotheses

- Underlying mechanisms are still controversially discussed in the literature
- Three selected hypotheses:
    1. Multi-circulation[1]
    2. Heat-pump analogy[2,3]
    3. Acoustic streaming[4]

[1]Xue, Y.; Arjomandi, M. & Kelso, R. (2013), 'The working principle of a vortex tube', *International Journal of Refrigeration* ***36(6), 1730 - 1740.***

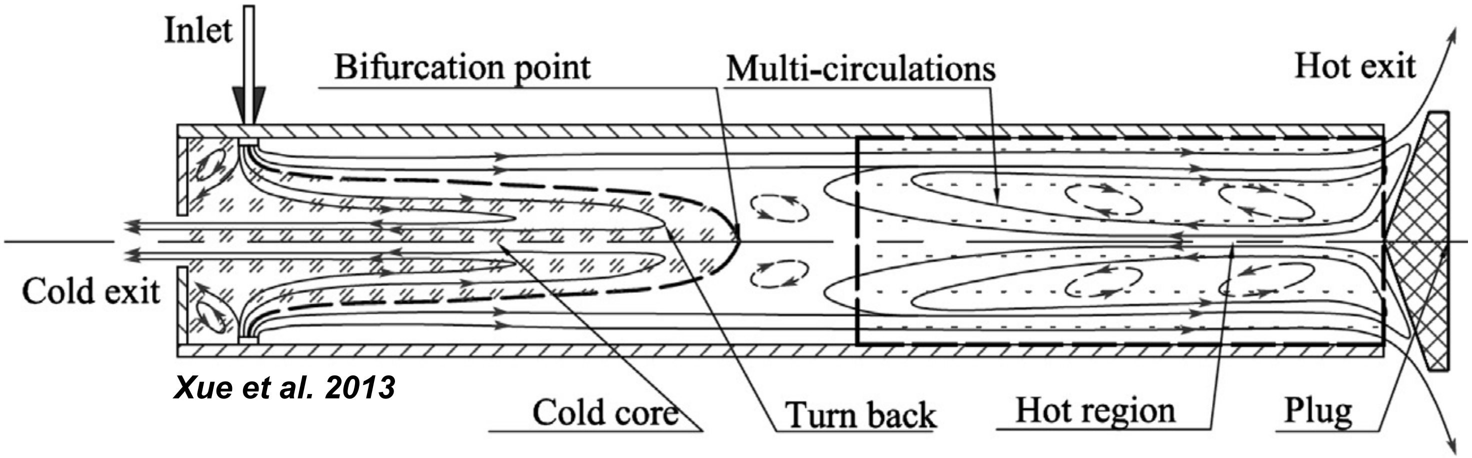
[2]Ahlborn, B. K. & Gordon, J. M. (2000), 'The vortex tube as a classic thermodynamic refrigeration cycle', *Journal of Applied Physics* ***88(6), 3645-3653.***

[3]Liew, R.; Zeegers, J.; Kuerten, J. & Michalek, W. R. (2012), '3D Velocimetry and droplet sizing in the Ranque-Hilsch vortex tube', *Experiments in Fluids* ***54(1).***

[4]Kurosaka, M. (1982), 'Acoustic streaming in swirling flow and the Ranque-Hilsch (vortex-tube) effect', *Journal of Fluid Mechanics* ***124, 139--172.***

Explaining the temperature separation | Multi-circulation (Xue et al. 2013**)**

- Flow expands from a high to a low pressure region → temperature drop in the tube's center
- Most of the peripheral flow exits the tube through hot exit
- Parts of the flow are forced back and enter a multi-circulation flow pattern → temperature rise at the hot end through interaction of central and peripheral (by partial stagnation and mixture)
- Cold core and the hot region are divided by a separating region → prevents mixing between front and rear



Xue et al. 2013

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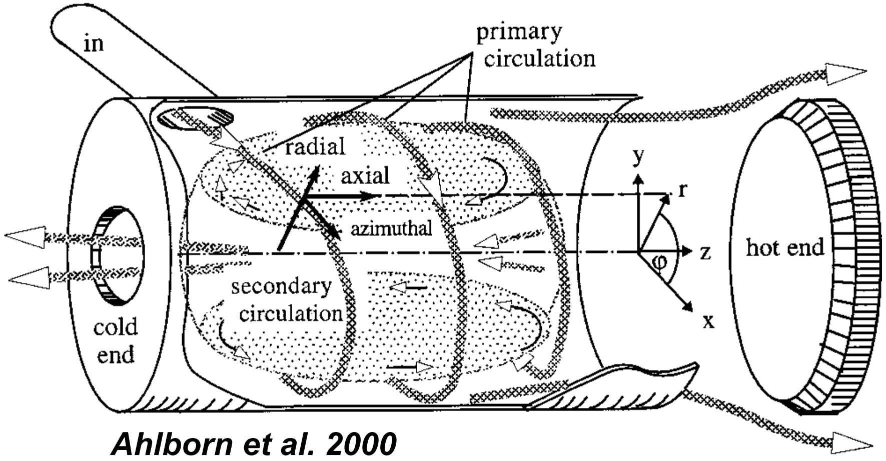
Explaining the temperature separation | Heat-pump analogy (Ahlborn et al. 2000, Liew et al. 2012)

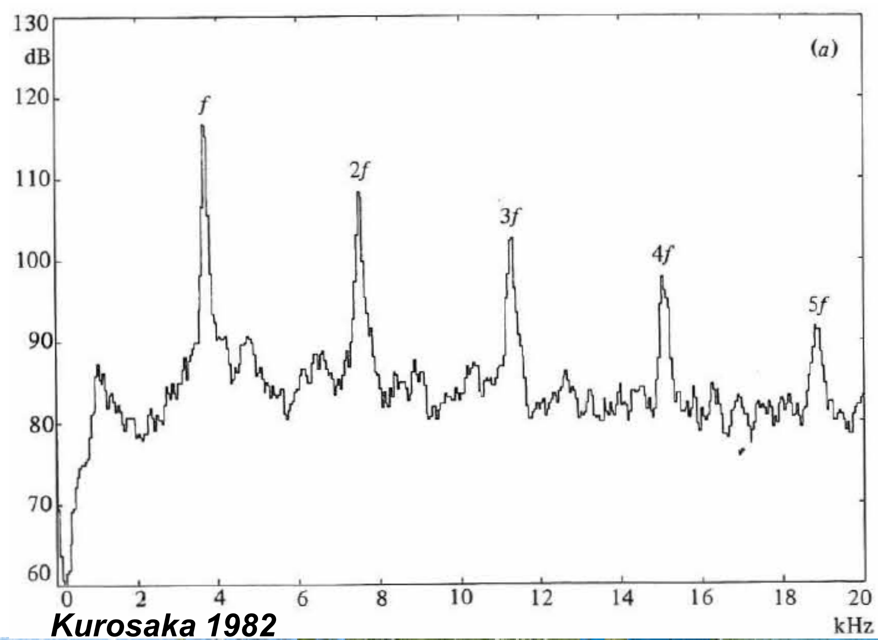
- Compressed air expands from nozzle → lowest temperature in the system
- Radial pressure gradient exists due to centrifugal forces
  → If gas is moved from the center towards the wall, it is compressed and heats up
  → If gas is moved from the wall towards the center, it is expanded and cools down
- Gas transport can only be maintained if radial velocity fluctuations are present
  → Ahlborn: secondary circulation
  → Liew: system of turbulent eddies



Ahlborn et al. 2000

Explaining the temperature separation | Acoustic streaming (Kurosaka 1982)

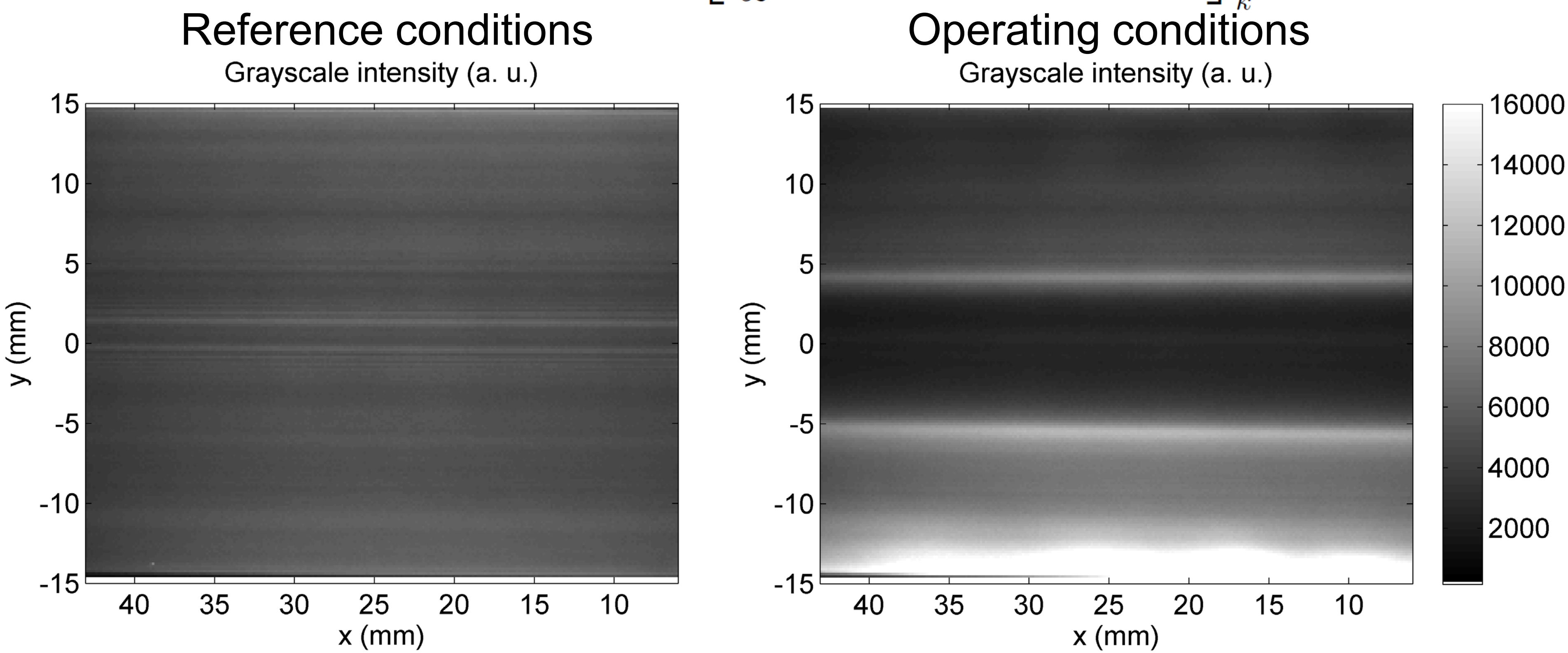
- Some form of unsteadiness is needed to explain the temperature separation
- Acoustic streaming: Distortion of the time-averaged flow field due to acoustic perturbations → Non-linear acoustics
- Experiment: A vortex tube was placed inside an acoustic cavity, sound pressure and temperature measurements at the centerline → fundamental frequency and higher harmonics
- Changing inlet pressure to modify f → when resonance of cavity is reached, SPL drops by 25 dB, temperature rises by 35 K



Kurosaka 1982

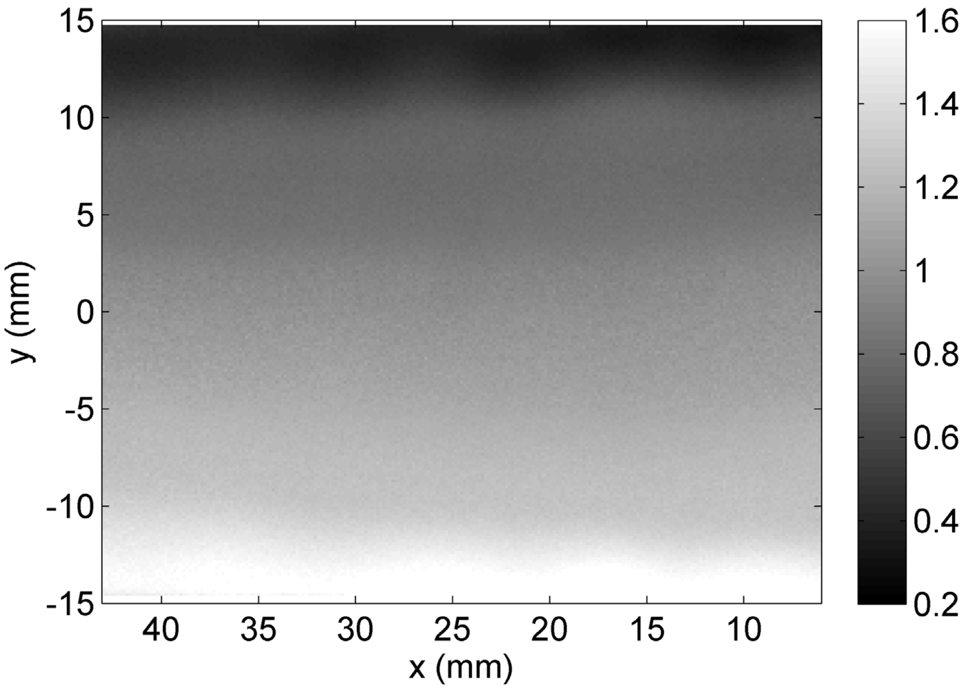
FSM-FRS technique and data evaluation methodology

$$S_{ijk}(X,Y,\nu_{0,k}) = R_{ij} I_0 \left(n_{ij}\sigma \left[\int_{-\infty}^{\infty} r_{ij}(X,Y)\tau(\nu+\Delta\nu_{ij})d\nu \right]_k + C_{t,ij} \right)$$



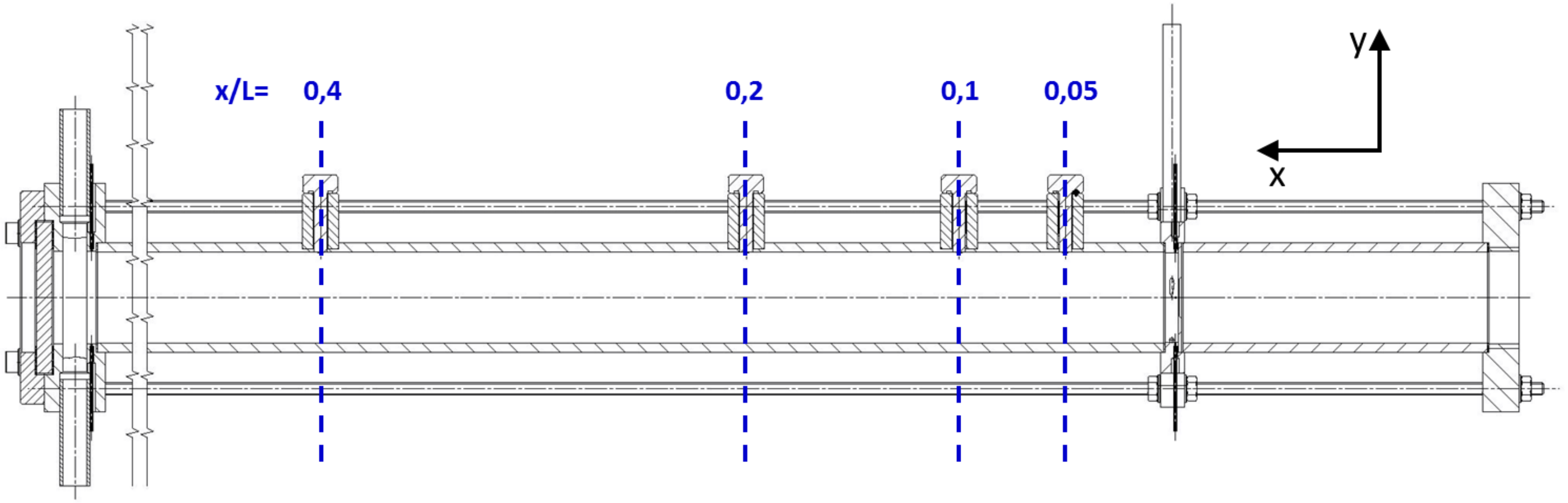
FSM-FRS technique and data evaluation methodology | Normalization

$$Q_{ijk}(X,Y,\nu_{0,k}) = \frac{S_{ijk}}{\langle S_{ij}\rangle} = \frac{n_{ij}\left[\int_{-\infty}^{\infty} r_{ij}(X,Y)\tau(\nu+\Delta\nu_{ij})d\nu\right]_k + C_{t,ij}}{n_{ij}\frac{1}{K}\sum_{k=1}^{K}\left[\int_{-\infty}^{\infty} r_{ij}(X,Y)\tau(\nu+\Delta\nu_{ij})d\nu\right]_k + C_{t,ij}}$$

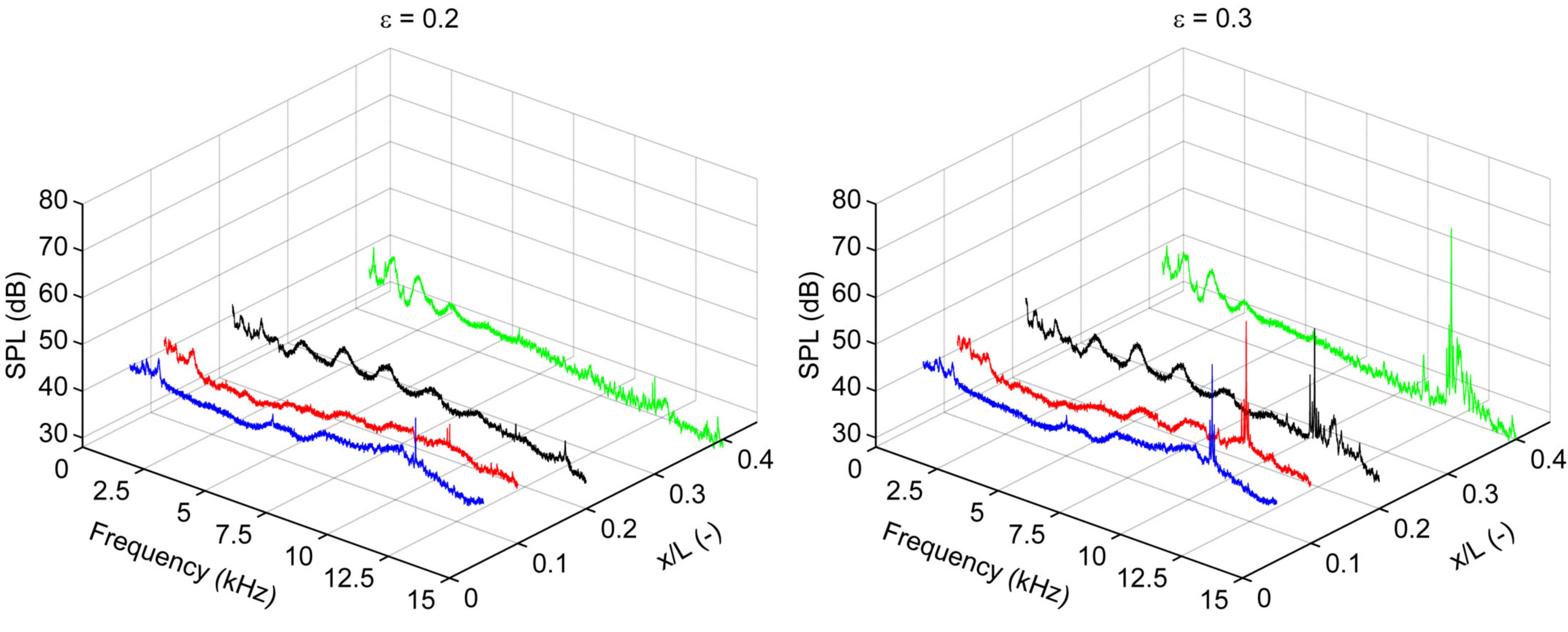


Global characterization | Setup

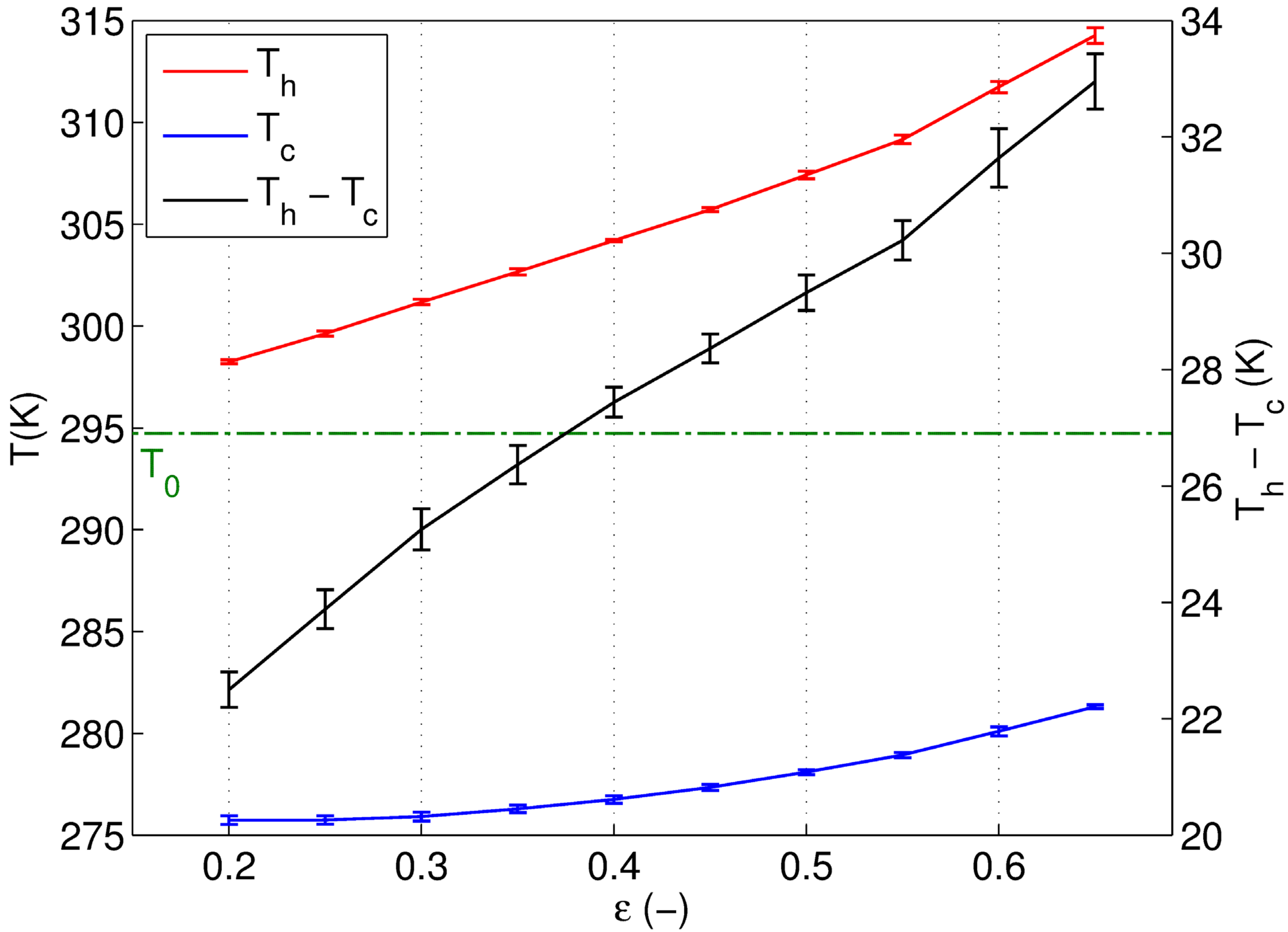
- Attributes influencing temperature separation:
  - Geometric properties: tube diameter (30 mm), tube length (700 mm), nozzle geometry, orifice diameter at cold exit
  - Inlet pressure (7 bar), inlet temperature (294 K)
  - Cold fraction $\epsilon = \frac{\dot{m}_c}{\dot{m}}$ → variation from 0.2 – 0.65
- Instrumentation → $\mathrm{p_0, T_0, T_h, T_c}$ (2 Hz, 90 s)
- Wall pressure with Kulite piezoelectric sensor (50 kHz, 60 s)



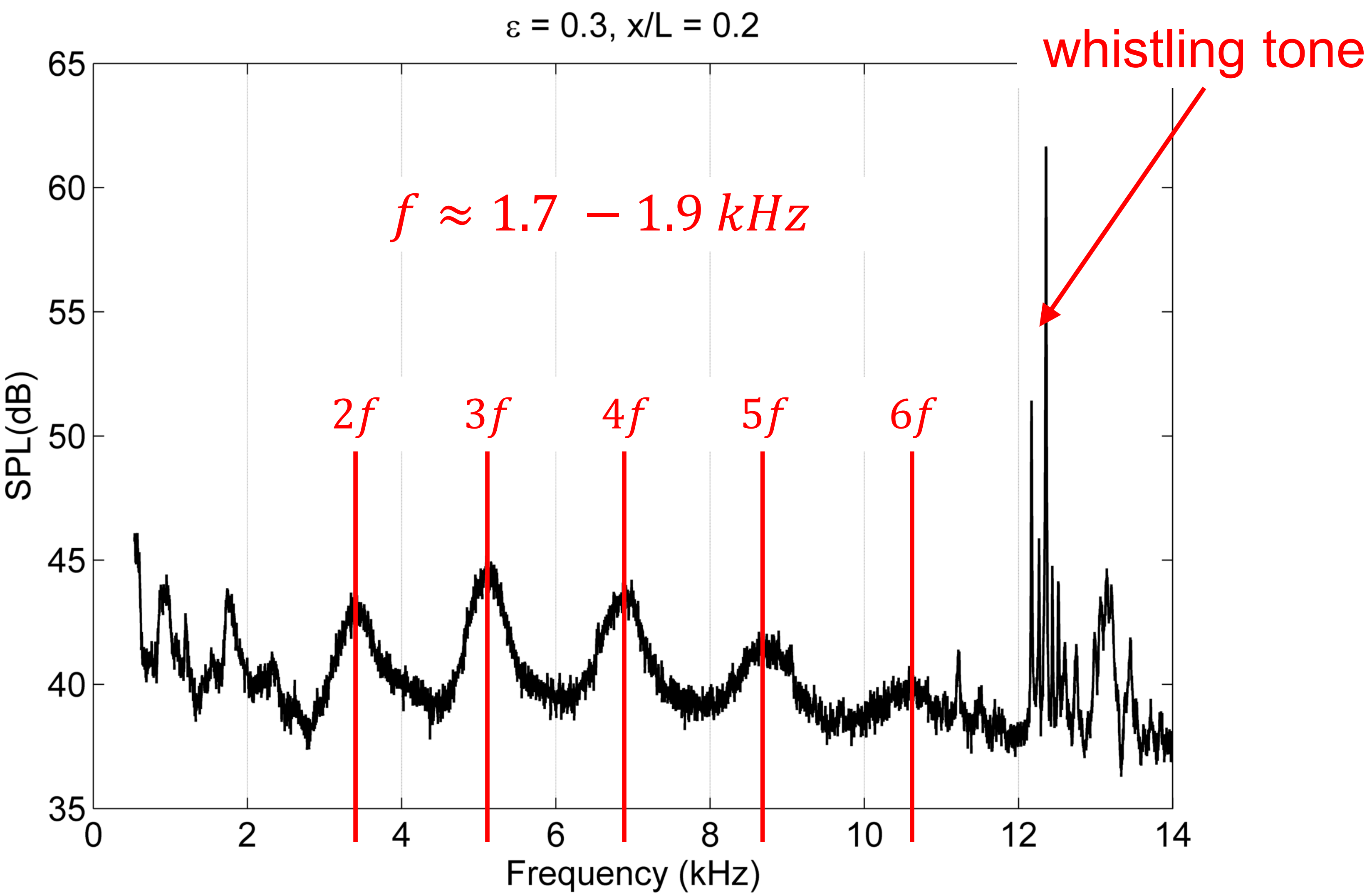
Global characterization | Frequency analysis



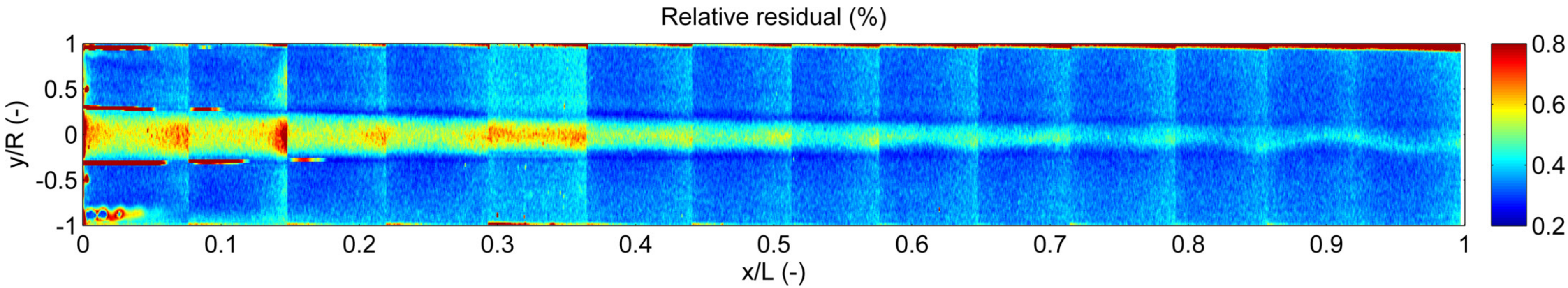
Global characterization | Temperature



Global characterization | Frequency analysis



FSM-FRS measurements | Relative residual



- Levenberg-Marquardt least-squares Method

$$\chi^2 = \sum_k \left(S_{k,Mod}\left(\nu_{o,k}\right) - S_{k,Meas}\left(\nu_{o,k}\right)\right)^2$$

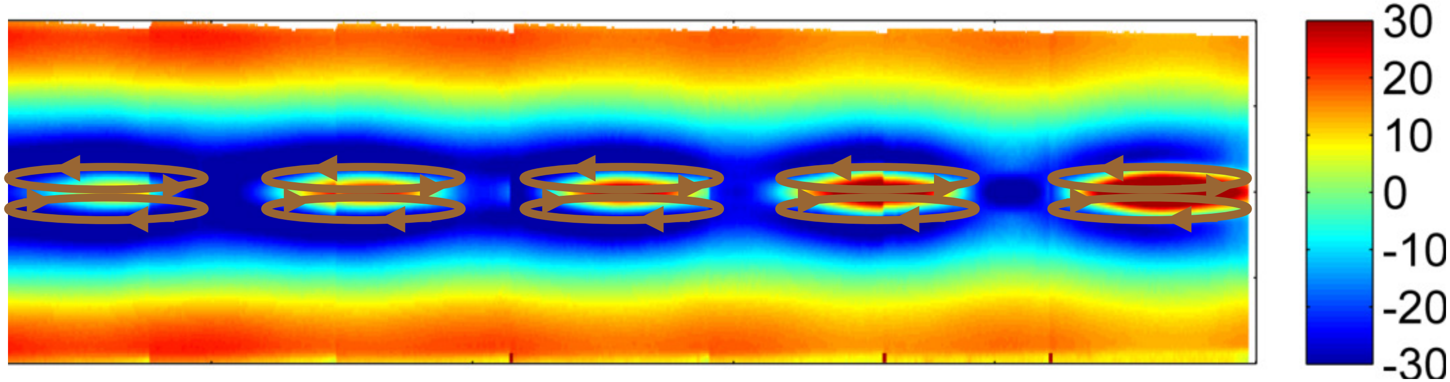
- Relative residual

$$\sqrt{\frac{\chi^2}{\sum_k S_{k,Meas}^2}} * 100$$

→ Measure for goodness of data fit

Discussion and summary

- Flow expands from a high to a low pressure region, formation of a cold core in the front (Xue et al., Ahlborn et al., Liew et al.)
- Cold core and the hot region are divided by a separating region (Xue et al.)
- Regular flow pattern:



→ Multi-circulation (Xue et al.) or heat pump (Ahlborn et al., Liew et al.)

- Acoustic streaming: Distortion of the time-averaged flow field due to acoustic perturbations